WHAT IS GOOD TEACHING OF COMPUTER NETWORKS?

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Abstract - *In this paper it is argued, based on theoretical as well as empirical grounds, that a university teacher in computer networks can improve students' learning by being aware of the different ways in which the students understand the concepts that he or she teaches. The distinct, qualitatively different, ways, in which students understand the network protocol TCP (Transmission Control Protocol), have been revealed in a research project, performed with a phenomenographic qualitative approach. The perceptions of TCP held among the students have been evaluated, based on situational appropriateness and richness. The results indicate that all the ways in which TCP is understood in the group are relevant during different phases of a software development project, and with different tasks at hand. Thus, a teacher should encourage students to understand what he or she teaches in different ways and should help them to choose in a relevant way between these perceptions. These results are also related to current research into students' learning, which clearly demonstrate that teaching, based on results of this type, promotes better understanding.*

Index Terms - Computer networks, computer science education, phenomenography, teaching methods

MOTIVATION AND OVERVIEW OF THE PAPER

What good, or meaningful, learning of computer networks is, and how it can be achieved, is discussed in this paper. The discussion is based on empirical research into how advanced university students, who take part in a project-based course, understand network protocols.

By studying how students understand network protocols, and by combining the results of this investigation with current research in theory of learning, conclusions are drawn about learning of network protocols. From here, we can go one step further and relate these results to the practical work performed in a software development project. The results then show that different ways of understanding the protocols are needed during different phases of the project. This serves as an empirically based, theoretically sound foundation for a discussion about good teaching of computer networks.

The empirical study into how students understand computer networks is performed with a qualitative phenomenographic research approach [8]. Qualitative research, its scope and limitations, and phenomenography are further described in the following two sections of this paper, which is followed by a section presenting the empirical study and its results. The theoretical perspective of learning, which is derived within the phenomenographic research tradition, and its implications for good learning form the core of the following section. The results of this study are analysed in the light of relevant theories, and conclusions, which serve as a basis for a discussion about what constitutes good learning, are drawn. These are presented in the section preceding the conclusions.

STUDYING LEARNING OF COMPUTER NETWORK PROTOCOLS

This paper presents the computer network protocol TCP[2], in the different ways in which the protocol is understood within a group of students. To do this investigation, a qualitative research approach (or research methodology), phenomenography [8], has been selected. It serves as a framework (or guideline, or "tool box") for the researcher in his or her efforts to reveal and study particular aspects of learning, here how students understand a network protocol.

Phenomenography can here be seen as a lens with a certain focus. It enables the researcher, as well as other members of the research community, to study certain aspects of the students' learning of TCP, while other aspects, outside of the focus of the lens, become unclear or "blurred". In the discussion about teaching of computer networks in this paper, the differences in how students understand the concepts that are taught, are in focus. That is, the different ways in which TCP is understood within a student population are explored, and conclusions are drawn about how these concepts should be taught. Again, these conclusions do not cover all aspects of a teaching situation, but rather those that are illuminated through the use of a certain research approach.

Qualitative research approaches, as phenomenography, are described in [5], p. 2 as

> "multimethod in focus, involving an interpretive approach to its subject matter. This means that qualitative researcher studies things [...] attempting to make sense of, or interpret, phenomena in terms of the meanings people bring to them."

Using a qualitative research approach, a researcher is thus offered tools to make interpretations of phenomena surrounding us. These interpretations are different from those that can be obtained in quantitative research. For some research questions, as this, a qualitative approach is more accurate, whiles in other cases a quantitative approach, or a combined approach, is more suited to address the research

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questions in relevant ways. Of course, other questions about the students' understanding of TCP can be investigated: Misconceptions, instead of understandings or perceptions, of TCP can be in focus; mental models describe differently an understanding can be researched; learning as a collaborative activity can develop our thinking; controlled experiments can help to make claims about particular mechanisms for teaching, just to mention a few relevant examples. All of these have to be researched in different ways, and offer thus different kinds of statements or conclusions about teaching and learning.

PHENOMENOGRAPHY AS AN APPROACH TO STUDY LEARNING

As was briefly indicated in the previous section, the research performed with a phenomenographic approach is exploratory and aims at describing and analysing the different phenomena from the students' perspective. The word phenomenography is derived from the Greek *phainemenon* (appearance) and *graphein* (description). Phenomenography is thus "concerned about the description of things as they appear to us" [10]. The phenomenographic researcher has the *students' experience of something* as his or her study object, and thus takes a second-order perspective.

Phenomenography is selected in this project since it offers, as was mentioned above, descriptions of a phenomenon (here TCP) as it is understood by the students. In other words, it is close to the students' different ways of understanding a concept, as well as to the concept they learn about, and does not presuppose particular structures or ways of thinking. Phenomenography offers rigorous, sound and well-researched ways to collect and analyse data, to describe the results, to deploy the results into the educational situation, and to judge to what extent the results can be trusted and generalised to other groups and other situations [8]. It has proved successful for studies of learning in higher education (see [1], [2] and [3] for examples within computer science).

Data for phenomenographic research is normally collected in semi-structured interviews. Students with different backgrounds, prerequisites, motivation etc. are selected for the interviews, so that a maximum of variation and richness is obtained within the whole set of interviews, the "pool of meaning", that serves as the principal source on which the analysis is based.

Although a phenomenon can be perceived in countless ways, phenomenographic research on learning claims that a researcher can organize these different perceptions into a limited, often rather small, set of categories. Each category then comes to summarize and describe a particular way of understanding a phenomenon. To obtain these categories the researcher has to analyse the "pool of meaning", containing all the interviews, in order to arrive at the set of qualitatively

different categories, together with a logical structure that relates these to each others [8].

The results of a phenomenographic research project should be interpreted at a collective level, with the individual students as "carriers" of one or many different ways of understanding something. The results are thus not tied to specific individuals or groups of individuals. Quantitative results are not in focus, since the continuous changes within the perceptions of a particular phenomenon makes statistical claims of little value.

EMPIRICAL STUDY OF STUDENTS' UNDERSTANDING OF A COMPUTER NETWORK PROTOCOL

As has been previously mentioned, this paper discusses good teaching of computer networks, based on an empirical study of students' understanding of some network protocols. The data for the empirical study stems from an open-ended project-based course that is given jointly by two universities in different countries [4], [6], [9]. The students work in teams of six, each team consisting of members from both universities. The technically advanced task they are assigned is rich on data communication issues and demands collaboration. Thus, during their work, the students have to discuss data communication issues with their team-mates both in their own country and overseas.

The Course Setting

During the course, each team of six students develops a software system that gives an end-user the possibility to "play" with a Brio labyrinth [1]. The labyrinth is a Swedish wooden toy, the aim being to manoeuvre a steel ball from a starting point to a final point on the board, by tilting it so that the ball moves without falling into any of the holes. The original labyrinth has knobs that are used to control the angle of the board, as is shown in the left hand picture of figure 1. The labyrinth used in the course is modified to have step-motors to control the board and a camera to give feedback to the controlling software system, as in the right hand picture. The camera and the step-motors are connected to dedicated computers.

The assignment demands good skills of computer systems. Particularly, the design of the modified toy contains several computer communication tasks, between the
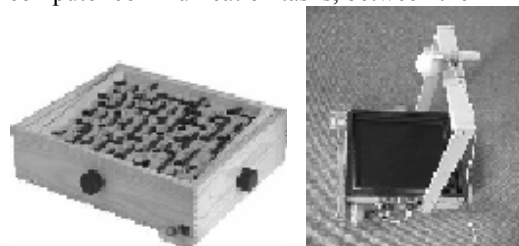

FIGURE I. A BRIO LABYRINTH IN ITS ORIGINAL FORM TO THE LEFT, AND IN THE MOTORIZED VERSION TO THE RIGHT

TABLE I. DIFFERENT WAYS OF UNDERSTANDING TCP DISCERNED WITHIN THE STUDENT COHORT

No	Category name	As what is TCP experienced?	As a part of which framework is TCP experienced?	What is the technical character of TCP?	How is TCP described?
1.	Safe communication	A protocol for safe communication	A framework of two specific computers	TCP is a protocol with acknowledgement	In concrete terms
2.	Connection	A setup connection	A framework of an internet	TCP is a protocol with acknowledgement	In an abstract way
3.	A standard	A standard for communication	A framework of a world outside the network	TCP is a protocol with acknowledgement	From an outside perspective

different components of the system, as well as in the communication with a web-browser. The choices how to tackle these, as well as the discussions about the relative advantages of different communication solutions and network protocols are important considerations during the students design of the solution. Later, during the coding, many of the problems that the students faced were related to computer communication.

Results on Students' Understanding of TCP

The results presented in this section are based on an analysis of interviews with approximately 15 students at two occasions [1]. During the interviews, the students were asked about different issues related to their experience of studying in this particular course, and the ways in which they understood some important computer network concepts. TCP was known for all students and had a clear role in the solutions presented by many of the student groups. These features of TCP have made the interview material rich, so a possibility to a thorough analysis has been offered.

Three different categories have been identified from data, each of them describing a distinctly different way of understanding TCP. The three categories together cover all perceptions of TCP found within the cohort. The categories differ not only in the meaning TCP, but also in other aspects, as the framework (or "scope") to which the protocol extents and the "level of abstraction" in which it is discussed. The characteristics of the categories are summarised in Table I. The categories are shown in the rows and the different aspects the columns. Below the categories are described in more detail.

1. **Safe communication:** Here TCP is described as a protocol for safe[3] communication between two specific computers that communicate, by sending packages of data. The protocol is talked about in concrete terms.
2. **Connection:** In this category an understanding is expressed where TCP offers possibilities to create connections over a network. Such connections are understood in the scope of an internet and are a part of

the network. The understanding of the protocol is here expressed in abstract terms. Packages are sent.
3. **Standard:** With TCP understood as a standard, it encompasses also the world outside the network, since a standard is decided by a committee. This is what gives meaning to the protocol. TCP is discussed from an outside perspective, but is still, in a technical sense, perceived as a package transfer.

As predicted by phenomenographic theory, a logical structure between the categories can be identified. The framework, as is indicated in the third column, of category 2 (an internet) encompasses that of category 1 (two computers), while in the same way the scope of category 3 is larger (a world outside computers). In a similar way, the level of abstraction of discussions increases between the categories, from being concrete (number 1) to discuss the network from an outside perspective (number 3).

As was mentioned above, the full set of categories form the background for the analysis. An example, which serves as an illustration of the interviews, can be found in Andy's statements[4] that clearly focus on two computers (category 1):

> Interviewer: What is TCP?
> Andy: That is ... you communicate with .. between client and server with TCP packets.

Here, Andy describes TCP as communication between two computers: a server and a client. In the continuation of the dialogue, the issue of safe communication is raised:

> Interviewer: What is a TCP packet?
> Andy: That's a type of packet, that one sends, that contains also ... so that one can get.... one must. It is a safe communication so that one knows ... three-way, so that one always knows it arrived or not, in contrast to UDP.

Andy here points out that TCP is a safe communication and says that TCP informs whether data, in the form of a TCP packages, has arrived or not. Also, by mentioning "three-way" he indicates that there is an acknowledgement sent by the receiving computer[5].

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[2] TCP stands for Transmission Control Protocols. Abbreviations are rarely spoken out within the field of computer communications. Acronyms are used as names of the protocols as well as the other entities discussed are discussed.
[3] The word *safe* is used as a synonymous to the word *reliable*, in order to keep closer to the terminology used by the students.

[4] The names on the students are changed in this paper to protect the anonymity of the students. Since there are few women taking the course, they are also given boys names in this paper.
[5] *Three-way* indicates in fact that there is an acknowledgement sent to confirm the arrival of the first acknowledgement. This technique is used when setting up a TCP connection between two computers.

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As has been stressed throughout this paper, the objective of this phenomenographic research project is to gain insights in the students' learning of computer communication. While the previous section of this paper has focused on the variations in the students' understanding of TCP, this section will discuss on how these insights can be used as a basis for improving learning in CS. This section leads forward to the coming, that discusses implications for teaching.

A Phenomenographic Perspective of Learning

A foundation for learning is, according to the phenomenographic theory about learning, that a student's perception of something is not static. Meaningful learning is a change in the learner's capability of experiencing something (TCP) in a new or different way [8]. This definition of learning does not only indicate that some learning is meaningful, but also points out that there are less relevant forms of learning. For example, rote-learning without a related deeper understanding, or learning of a new program construct that does not offer any new possibilities to develop thinking or programming, are not examples of meaningful learning.

In the phenomenographic perspective the student interacts with the phenomenon he or she is studying. His/her understanding of the phenomenon is then shaped by the phenomenon in its context, but also by the student him- or herself with his or her interests and previous understandings. Thus, to discuss what constitutes a good understanding, and how the universities can act to promote this, both the subject area and the students themselves must be taken into account.

Marton and Booth also discuss good learning and argue that the ways in which learning is experienced "differ in *richness* (different aspects of learning that are discerned and held in focus simultaneously) and *situational appropriateness* (which particular aspects held in focus under the prevailing conditions)." ([8], p. 55, our italics). This will be taken as a starting point for a discussion on good learning of network protocols.

Situational Appropriateness of Ways of Understanding Network Protocols

The phenomenographic perspective, describing the different perceptions or understandings of something that exists within a group, invites to a further study of in which situations, and why, these perceptions are relevant, that is, studies of their *situational appropriateness*. An analysis of the situations in which the three categories are relevant in the work of programmer or program designer has been made and is summarized in Table II.

Experiencing the protocol as safe communication between two computers (category 1) is closely related to programming. The students' descriptions of TCP resemble the terminology that is used in different programming situations that relates to data communication. It can be assumed that this perspective is fruitful for solving concrete programming issues.

A quote from Sebastian can illustrate this. On a question from the interviewer about UDP, he compares UDP and TCP:

Interviewer: UDP?
Sebastian: UDP.... but that is another form of communication. TCP/IP is set up ... like TCP, in contrast to UDP, TCP sets up communication between two points, and they talk to each other and make sure that they don't drop anything sort of.

Sebastian here discusses TCP in concrete terms as a protocol for safe communication between two computers.

The protocols TCP and UDP are not only formal descriptions of how computers communicate, but they also offer procedures, or operations, to a programmer who writes application programs. The TCP software offers services like setting up connections or sending data. The statements by Sebastian above can directly be related to programming issues for using TCP in an application program. Similarities between his statements and some basic operations on TCP sockets are shown in Table III.

Understanding TCP as a way to create connections over an internet, of which the protocol is integrated part (category 2), is useful for discussing the properties of TCP. Issues like in what situations and in what way a protocol is useful come into focus here. It can thus be assumed that this way of experiencing a protocol is fruitful for design purposes.

Allan stresses that TCP is a part of an internet, and discusses what TCP "is":

Interviewer: Um, you've talked about TCP. What is TCP?
Allan: Basic concepts.. it's a protocol language, I guess you can call it, that you just put your data in and it's sent across the network using the different protocols you want to use, like IP or.. I can't think of any other protocols off my head. But it is more or less a packet that you put your data in and you send across and it has some features such as, keeps things in order when you, um, when you get to the, um, when it gets to the server you want to go to.

He says that TCP is a protocol language[6] that is used for sending data across a network. He also explains its main feature, as he perceives it: The order of data is kept when sent to the application program through the TCP socket[7], although data physically might have arrived to the server in any order. He focuses on what the purpose of using TCP is. This understanding is useful for deciding when to use TCP, and when to choose another protocol.

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[6] The term *protocol language* refers to a formal language. A formal language is used to express statements about calculations in a general sense.
[7] A TCP *socket* is an endpoint of a connection between two computers originally created in a Unix environment. It is used by a programmer as a mechanism for transferring data.

TABLE II. RELEVANCE OF THE DIFFERENT WAYS OF UNDERSTANDING TCP

No.	Category name	Category description	Field of relevance
1.	Safe communication	A protocol for safe communication between two specific computers described in a concrete way	Programming tasks
2.	Connection	A setup connection that operates over an internet, and is discussed in abstract terms.	Design, such as selection of overall structure of software systems based on computer communication solutions
3.	Standard	A standard for communication, discussed from a perspective outside the network.	Future development of computer communications, such as new needs for and properties of network protocols

Discussions from an outside perspective, that concern what properties protocols could have, characterise an understanding that is described in the third category. This understanding is useful for policy discussions.

In this section it is argued that different ways of experiencing network protocols are useful for different tasks at hand. The examples given above are intended to illustrate the relevance of being capable of understanding TCP in different ways. Other applications of the different understandings of TCP certainly exist, and the applications proposed here does not need to be the principal situations when a particular way of understanding the protocol is useful. However, already these glimpses into data demonstrate that the three categories all describe useful ways of understanding TCP, and that they are applicable in different situations. Good teaching of TCP should thus promote that the students understand what is taught in different ways.

Richness in Ways of Understanding Network Protocols

Marton and Booth argue that good learning is characterized by situational appropriateness (as discussed in the previous section) as well as *richness*, which is defined as a capacity to understand something in different ways at the same time.

When solving a problem various tasks and sub-task have to be performed, each demanding different skills and perspectives on the task. For solving complex or new problems within computer networks, and to judge the relevance or quality of a solution, it is necessary to adopt different ways of thinking about the network concepts, now as a programming task, then as a standard. Thus, when developing communication applications, richness in the understanding of the protocols involved is advantages.

During the interviews, some students discussed TCP in different ways, shifting between different perceptions of the protocol. Of course, not all students did this, as some of them only understood TCP in one way, the least complex way, as a safe communication between two computers.

An example of such a shift from perceiving TCP as communication between two computers, expressed in concrete terms, to perceiving the protocol as related to an internet, expressed in abstract terms, can be found in an excerpt of an interview with Anthony:

> Interviewer: Uhum. What is TCP?
> Anthony1: TCP is another type of protocol .. used between two machines. There is TCP and there's UDP that's one of the things that I actually do remember from ah, networking class. And I believe TCP sends packets to one machine and then there is some sort of response saying that they got the packets or not [...]

Here Anthony expresses an understanding where TCP is used for the concrete purpose of sending packages. TCP offers a response that indicates whether a package has arrived or not, that is, TCP has an acknowledgement. The dialogue continues:

> Interviewer: So what's the implication of this?
> Anthony1: Um, it, it all depends on how you're coding it. It depends on how secure the network you're on. And if you actually trust just sending it out and just assuming that it gets there

When the discussion continues Anthony gets a question about the implications. He argues that the implications depend on how "you are coding it", that is, what your program actually does, and your understanding of the quality of the network. His focus changes here from the packages sent between two machines to TCP as a part of a network that he assigns abstract properties, like trust. In this case the shift was triggered by the interviewer asking a question that encouraged the student to reflect further on the subject.

The full set of interviews are rich on shifts of this kind, either spontaneous or trigged by the on-going discussion led by the interviewer This indicates that some students easily go between different ways of thinking about TCP, that is, they have a rich understanding of the protocol.

TABLE III. SIMILARITIES BETWEEN SEBASTIAN'S STATEMENTS ABOUT TCP AND BASIC TCP OPERATIONS

Sebastian's statements	Basic TCP operation
set up	Connect to a remote machine
talk to each other	Send data
talk to each other	Receive data
implicit, a connection that is set up, also has to be closed	Close a connection

IMPLICATIONS FOR TEACHING

In the previous section argued it is that a good understanding of TCP is obtained when the students understand TCP in several ways, and can freely choose how to think about TCP in a particular situation. In this section the argument will be taken one step further, by suggesting how a teacher could promote good understanding by offering variation in the ways network protocols are taught.

The point of departure here is research on how variation in teaching, based on empirical phenomenographic results on learning, can be used as a resource to enhance student learning. Pang [10] has made an interesting study on the effects of teaching economics inspired by phenomenographic research. First, he investigated the different ways in which the students understood a particular concept, price elasticity. Then two groups of teachers were asked to teach their respective classes in different ways: one group of teachers was asked to base the teaching on the phenomenographic results on students' understanding of price elasticity, while the other group of teachers taught in a traditional way. Students in the theory-inspired group demonstrated a better understanding of the topic than their counterparts in the comparison group. The results were striking: During the student interviews and some of the test tasks, twice as many students in the theory-inspired group understood the concepts in congruent with the expectations of the teachers. Pang's well-made study is not unique; his results are consistent with the findings of other phenomenographic research projects (for example [7], [11], [12]). It can thus be assumed that his conclusions, based on studies in economics, can be transferred to similar settings also where computer science is studied.

A conclusion can be drawn: A variation in the presentation of a concept that is based on the different ways in which it is understood improves learning. A first implication of this conclusion is that a teacher of computer networks should create a variation in how he or she presents the concepts. This variation should be based on the ways in which the students, at a collective level, can understand that particular phenomenon.

An example of how this theory can be applied is to present TCP as a connection over an internet during the lectures, give the students a closed lab that aims at giving them hands-on experience of communication between two computers, as well as an open-ended essay question, where the students are asked to judge certain features of TCP. Finally, in this scenario, they can be given an open-ended group project, where they need to make over-all decisions, design a program, code it, and then finally evaluate it the result. Taught in this way, both the content and the teaching forms have been varied. The critical, or important, variation is not in the kind of assignments that are given, but in the ways in which the students are encouraged to think about the protocol.

CONCLUSIONS AND FURTHER RESEARCH

By creating a variation in teaching of computer networks, a better learning among the students is promoted. Teaching should be based on the ways in which students, at a collective level, can be expected to understand the concepts taught. The three different ways in which TCP is understood, have been demonstrated to be useful during a software development project. The results presented in this paper have thus direct applications in teaching situations in computer networks, both teacher-led teaching situations and project work, as well as in a larger context in research about learning and curriculum design. Future research will investigate how students, who study in project teams, can be encouraged to understand the phenomena they study in different ways, and which factors in the learning environment that promote or hinder meaningful learning. A result of this research will be a framework of recommendations on the design of computer science projects so that they promote good learning.

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